VERTICAL DATUM TRANSFORMATIONS FOR KINEMATIC GPS HYDROGRAPHIC SURVEYS

Kurt W. Hess, Dennis G. Milbert, Stephen K. Gill, and Daniel R. Roman

National Ocean Service, NOAA

ABSTRACT

Kinematic Global Positioning System (KGPS) hydrographic surveying measures the elevation of the sea bottom relative to an ellipsoidal reference frame, but the National Oceanic and Atmospheric Administration's (NOAA's) nautical charts depict water depths relative to mean lower low water (MLLW). NOAA has developed software for the conversion of elevations from a three-dimensional (ellipsoidal) datum to MLLW. The software, VDatum, uses a four-step process: (1) transforming elevations from the ellipsoidal datum to the NAD 83(86) three-dimensional datum, (2) transforming elevations from the three-dimensional datum to the NAVD 88 orthometric datum, (3) transforming from the orthometric datum to local mean sea level (LMSL), then (4) from LMSL to MLLW.

VDatum was used to process data from a recent (June 6-7, 2001) KGPS hydrographic survey in Delaware Bay. The first two transformations have been previously developed for the coterminous U.S., but the second two were generated specifically for this application. The NAVD 88-to-MSL field, called the sea surface topography, was generated by spatial interpolation of values at GPS-referenced tidal benchmarks. The tidal datum fields relative to LMSL for Delaware Bay were created by NOAA's TCARI (Tidal Constituent And Residual Interpolation) model from values at present and historical water level stations where analyzed datums were available. The Delaware Bay test indicates that the use of VDatum with KGPS is likely to produce bathymetric data of higher accuracy than that available from the presently used methods.

NOAA is presently planning for the development of a National VDatum software tool.
The tool would have a database structure that can access multiple VDatum grids, depending on the specific location. NOAA has plans to install temporary water level gauges in certain coastal areas to re-establish tidal datums, and to ellipsoidally reference key gauges. NOAA is also planning to develop and apply a suite of tidal models to generate tidal datum fields for all U.S. waters.

INTRODUCTION

The promise of Kinematic Global Positioning System (KGPS) hydrographic surveying is that it can measure the elevation of the sea bottom relative to an ellipsoidal reference frame, and that this bottom elevation value can be directly applied to a nautical chart. At present, however, the National Oceanic and Atmospheric Administration's (NOAA's) nautical charts depict water depths relative to mean lower low water (MLLW). Therefore, ellipsoidally-referenced depths

must be converted to the MLLW reference elevation. This conversion can be accomplished either by tide zoning or by the use of NOAA's vertical datum transformation software, VDatum.

VDatum, developed by NOAA's National Geodetic Survey (NGS) (Milbert, 2002), converts elevations from a three-dimensional (ellipsoidal) datum to MLLW and requires a four-step process. The steps consist of (1) transforming elevations from the ellipsoidal datum to the three-dimensional datum NAD 83(86), (2) transforming elevations from the NAD 83(86) datum to the NAVD 88 orthometric datum, (3) transforming from the orthometric datum to local mean sea level (LMSL), then finally (4) transforming from LMSL to MLLW. The first transformation is made using geometrical relationships, and the second is performed by application of NOAA's GEOID99 model (Smith and Roman, 2001). The NAVD 88-to-LMSL surface can be generated by spatial interpolation of values at tidal benchmarks. The LMSL-to-MLLW field can be computed from hydrodynamic tidal models, spatial interpolation of gauge-based tidal datums, or a combination of tidal modeling and interpolation of errors. Provided that the NAVD 88-to-LMSL and tidal datum fields have been generated, all these transformations can be accomplished seamlessly using VDatum (Figure 1).
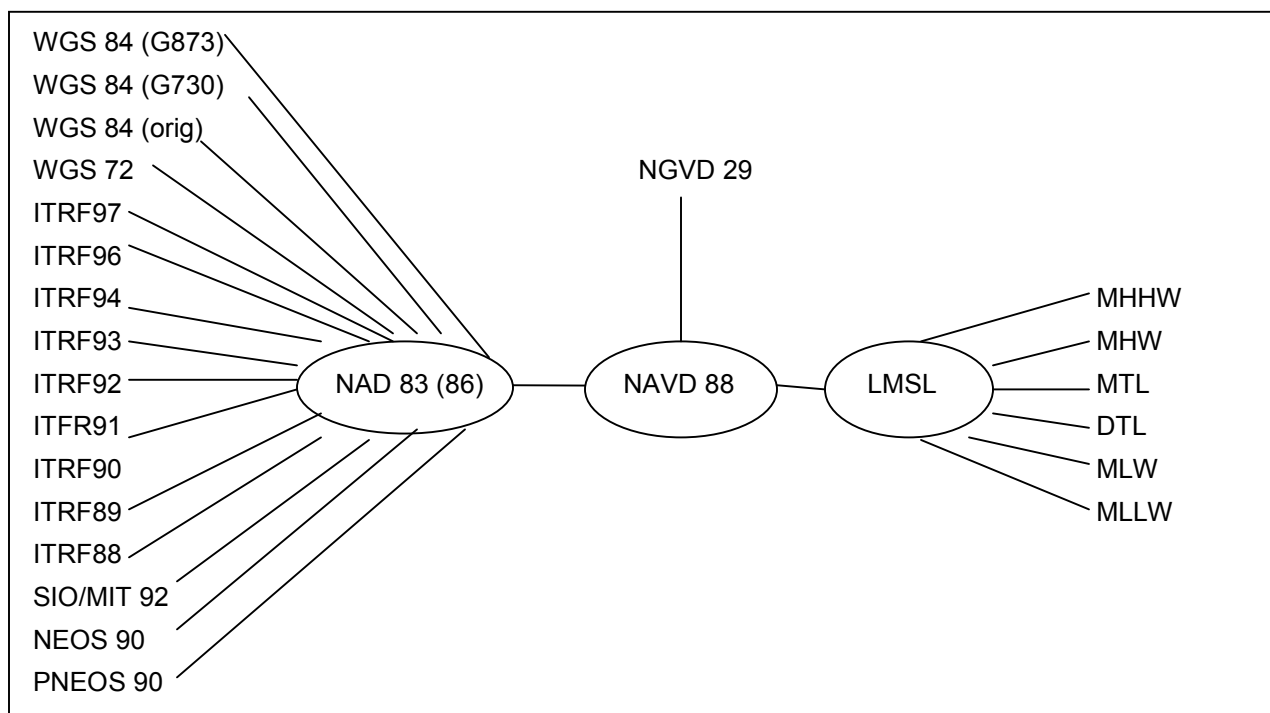

Figure 1. The VDatum 'roadmap.' Transformations can be made from elevations in any of the three-dimensional fields in the column on the left side to NAD 83 (86), then to NAVD 88, then to LMSL, and then to any tidal datum in the column on the right side. There is also an NAVD 88-to-NGVD 29 transformation. Straight lines represent transformations.

Tidal datum fields have many uses in addition to processing hydrographic surveying data. Tidal datum transformation fields can also be used in the tide corrections of traditional soundings.

2

They can help in generating shorelines by simulating the MLLW and MHW fields along coasts, which are used by NOAA to plan the timing of photogrammetry and LIDAR surveying. Finally, tidal datum fields can be used to re-reference NOAA's historical bathymetric data to standard elevation frames for integration with land elevations into seamless digital elevation models (DEMs). When a tidal datum is selected, a DEM can then be used to produce a datum-defined shoreline within a single vertical reference frame.

VDatum was used to process data from a recent (June 6-7, 2001) KGPS hydrographic survey in Delaware Bay (Riley and Milbert, 2003). The Delaware Bay test showed that numerous cases of 5- to 15-cm departures of the GPS-controlled data from the data processed in the standard way was due in the standard processing to a discontinuous tide correction when crossing a tide zone boundaries. The next two sections of this paper will focus on the definition of tidal datums and how tidal datum fields can be modeled. Following that, the development of the NAVD 88-to-LMSL and tidal datum fields for Delaware Bay will be discussed. The last section will describe plans for a national application of VDatum.

TIDAL DATUMS

Tidal datums at water level gauges are elevation values that are determined from a time series of observations (Gill and Schultz, 2001). For NOAA's gauges located along the coasts of the U.S., the data are collected by NOAA's Center for Operational Oceanographic Products and Services (CO-OPS). The analysis of the water level data by CO-OPS is based on (except for the Great Lakes) the identification of all the tidal extrema (highs and lows), and the selection (within a 25-hour or so time period) of the higher of the two highs and the lower of the two lows (Figure 2). If only one high water is found, it is categorized as a higher high. The average of all the highs and higher highs is called the Mean High Water (MHW), and the average of just the higher highs is called the Mean Higher High Water (MHHW). The process for producing Mean Low Water (MLW) and MLLW from the low waters is similar. The average of the MHW and the MLW is called the Mean Tide Level (MTL) and the average of the MHHW and the MLLW is called the Diurnal Tidal Level (DTL). Mean Sea Level (MSL) is the average of the hourly water levels. Where MSL is not computed, the MTL or DTL can be used as approximations.
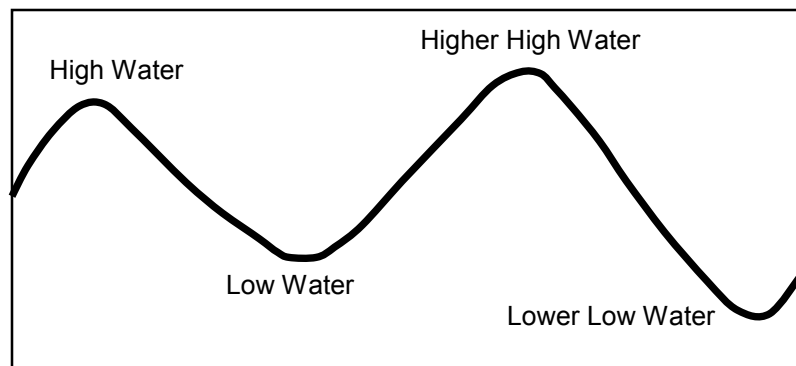

Figure 2. Schematic showing a typical observed water level (solid line) for one day with the two high waters and two low waters denoted. For the time period shown, the higher of the two highs is called the 'higher high water' and the lower of the two lows is the 'lower low water.'

Observations made in a limited time period are adjusted to represent the values for a 19-year National Tidal Datum Epoch; at present, the epoch most commonly used is 1960 to 1978. More recent epochs are required for locations where apparent sea levels are changing rapidly due to local land subsidence or isostatic rebound following the last ice age. The datum values at NOAA water levels gauges are routinely computed by CO-OPS and are available to the public on the station benchmark sheets.

Much as the tide varies from place to place, tidal datums can vary considerably over the survey area, thus giving them the characteristics of two-dimensional fields whose values change with horizontal position. In central Delaware Bay, the change in MLLW is about 1 cm/nmi; the change is more dramatic in other U.S. coastal regions. Therefore, using a constant value for a tidal datum in the survey area can lead to errors in processing hydrographic data.

MODELS OF TIDAL DATUM FIELDS

Tidal datum fields can be generated from the output of numerical hydrodynamic tidal models, or by spatial interpolation of water level gauge data. Numerical models can incorporate local bathymetry and tidal physics, but require intensive computer resources and typically take months to years to reach an acceptable level of accuracy. Spatial interpolation can be applied relatively quickly, but works best in regions where extensive observational data are available.

Where a numerical circulation model is available, a datum field can be generated as follows. First, a long (1 year) simulation is completed and water levels at 6-minute intervals are saved at all model grid cells. Next, the time series at each cell is analyzed to pick off amplitudes of high waters, higher highs, low waters, and lower lows. Then the amplitudes are averaged to get the MHHW, MHW, MLW, and MLLW values at all cells. The LMSL field is computed by averaging the 6-minute values at each cell. The two-dimensional field for each datum is represented by the values at the cells. This process was used by NOAA's Office of Coast Survey (OCS) in Tampa Bay, Florida (Hess, 2001).

Another method of water level prediction is by the use of a tide model that interpolates tidal data to locations between the gauges. The Tidal Constituent And Residual Interpolation (TCARI) model (Hess, 2003; Hess, 2002; Hess et al., 1999) was designed for estimating astronomic tides and total water levels at selected locations along the coast by the spatial interpolation of tidal data. The model spatially interpolates the harmonic constants (used to predict astronomic tide), tidal datums, and residual (or non-tidal) water levels (i.e., the difference between the astronomically predicted tide and the observed water level) using the values at a combination of operational and historical stations. The method works best in regions where there is an abundance of high quality tidal data. TCARI was specifically formulated to overcome the problem of interpolating tidal data from nearby water level stations that are separated by land (such as a barrier island), where large differences in tidal amplitudes and phases at closely-spaced points would make application of the usual interpolation schemes problematical

DATUM TRANSFORMATION FIELDS FOR DELAWARE BAY

The first step in applying VDatum to Delaware Bay was to get the NAVD 88-to-LMSL transformation field. This was done by NGS using optically-referenced water level gauges at various locations along the shore of the bay, and interpolating the NAVD 88–to-LMLS difference field using a minimum curvature algorithm. The water level data at the gauges were measured by CO-OPS, which also developed the tidal datums. Based on the interpolated field, there is a decrease in the NAVD 88-to-LMSL difference of about 0.1 m as one progresses from the mouth of the Bay northwestward (Figure 3). This change represents an increase in the mean water surface that is due to steric effects, that is, a change in water density due to a decrease in salinity.
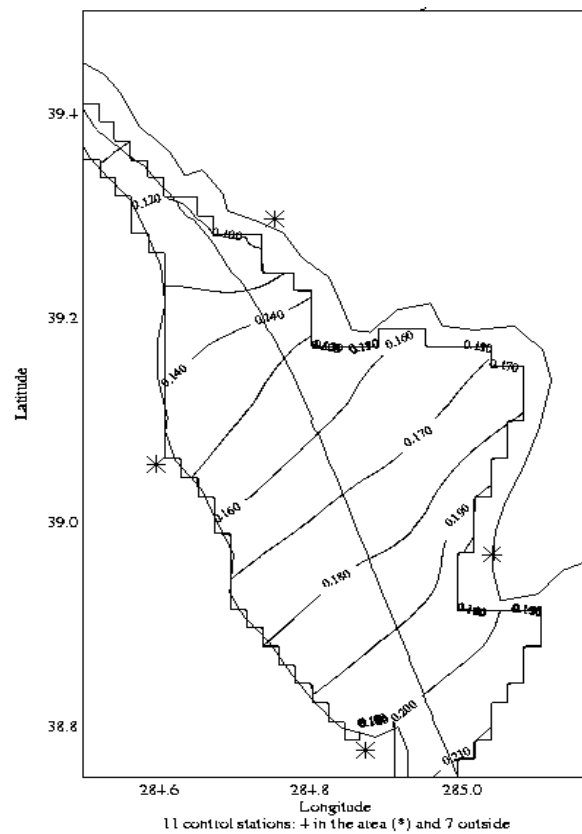
Figure 3. The NAVD 88-to-LMSL difference in Delaware Bay (m). LMSL was below NAVD 88

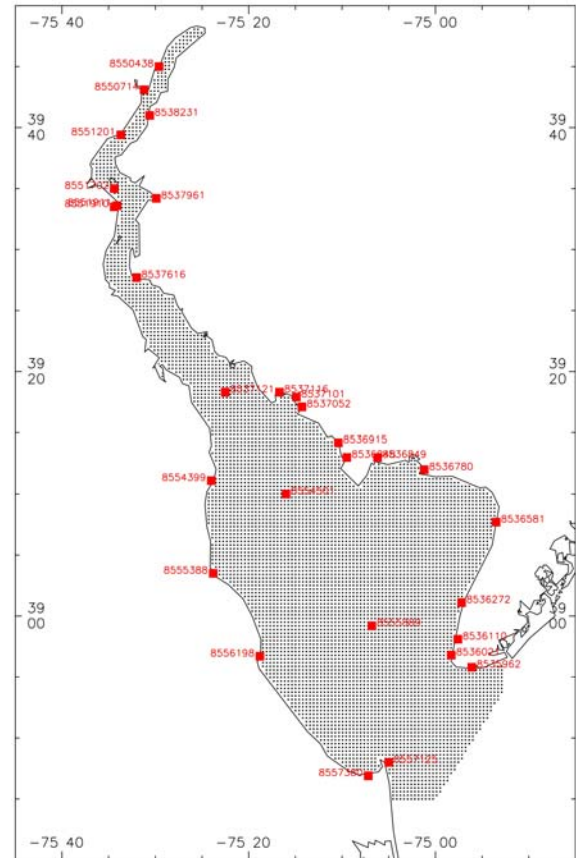by 0.20 m at the entrance (lower right) and 0.11 m in the upper left.

Figure 4. TCARI grid (closely spaced black dots) and tidal datum locations (numbered red

squares).

Tidal datums fields were generated in OCS by interpolation of data at shore locations with the application of TCARI to Delaware Bay. The first step was the creation of a uniform grid with a cell size of 0.3 nmi, which is small enough to resolve the coastal features of interest such as the Delaware River. A digitized shoreline, obtained from NOAA's National Geophysical Data Center, was then used to select cells that represent water (Figure 4). Tidal data at 29 water level gauges in Delaware and New Jersey were used (Figure 4). A plot showing the resulting TCARI distribution of MLLW (relative to LMSL) is shown in Figure 5. It is usually difficult to check these distributions against observational data since tidal datum fields are generally unknown. However, the distribution of the mean tide range (MHW minus MLW) visually matches well with numerical-model generated ranges for the Bay (NOS, 1987).
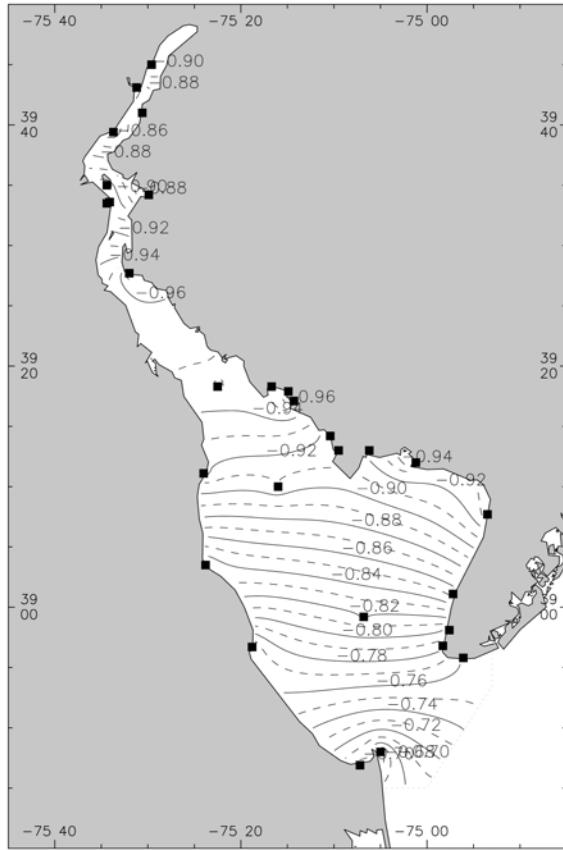
7

Figure 5. MLLW (m) relative to LMSL from the TCARI interpolation. Black squares denote water level gauges used.
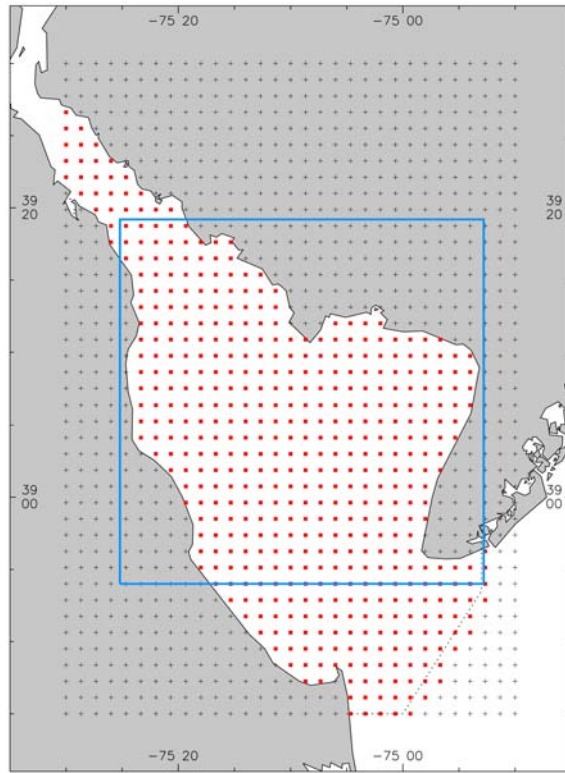
Figure 6. The VDatum grid. Points (red) denote water and the crosses (black) are null values. The blue line denotes the limits of the NOAA survey.

The gridded tidal datum fields used in VDatum (one each for MHHW, MHW, MTL, DTL, MLW, and MLLW, all relative to MSL) were generated by interpolation of the tidal data from the tidal grid. The VDatum grid (Figure 6) has an origin at 38.75 N and 75.50 W, and the interval between points is 0.0187500 arc-degrees (1.125 nmi) in the vertical and 0.0222222 arc-degrees (1.036 nmi at 39 N) in the horizontal. The resulting array is dimensioned 41 by 31. The exact values for the origin and increments are somewhat arbitrary, but they provide coverage of the whole water area of the lower Bay at a resolution sufficient for hydrographic surveys. Values at each point in the VDatum grid were determined by taking the average of all tidal datum values from the tidal grid within a radius of 0.02 arc-degrees (appx. 1.2 nmi), provided the VDatum point lies within the water area as delineated by the digitized shoreline. Points outside the water area or tidal grid were given null values. When using VDatum, tidal datum values at any specific location within the VDatum grid are obtained by either bilinear interpolation from four surrounding non-null values, or by quadratic distance weighting if there are from one to three values non-null values.

TOWARD A NATIONAL VDATUM

As mentioned above, VDatum only works in locations where the NAVD 88-to-LMSL field and the tidal datum fields have been generated. At this time, NOAA's work has been limited to Tampa Bay, the New York Bight, southern coastal Louisiana, Delaware Bay, and central coastal California. However, NOAA is presently planning for the development of a National VDatum software tool.

In the future, NOAA plans to develop a database structure that can access multiple VDatum grids such as that shown in Figure 6, depending on the specific geographic position. Individual VDatum grids would be developed for each coastal bay or region of interest, with the grid spacing dependent upon the scale of geographic features (such as barrier islands) needed to be resolved. CO-OPS has plans to install temporary water level gauges in certain coastal areas to re-establish tidal datums. Some coastal areas have not been measured for decades, and changes in land elevations due to subsidence or isostatic rebound, and changes in coastal features due to subsidence or erosion can affect tidal characteristics. NGS and CO-OPS will work together to ellipsoidally reference key gauges. OCS is planning to develop and apply a suite of tidal models to generate tidal datum fields for U.S. waters within the Exclusive Economic Zone (EEZ).

For generating tidal datum fields, the proposed, tiered approach would start by developing a suite of ocean-scale (e. g., Western North Atlantic Ocean, Eastern North Pacific Ocean, Gulf of Mexico, Arctic Ocean, Tropical Pacific) models. The proposed hydrodynamic model is the two-dimensional Finite Element Model (FEM), ADCIRC (Luettich et al., 1992). This model was used to generate tidal constants for the U.S. East Coast (Mukai et al., 2002) and was used for inverse tide modeling in the eastern North Pacific (Myers and Baptista, 2001). The grids for ADCIRC consist of triangular cells of various sizes and are adept at capturing small coastal features and can be altered or added to with little difficulty. The two-dimensional version of ADCIRC is sufficient for capturing the major tidal hydrodynamics. Next, the ocean-scale model results would be used to drive a set of higher-resolution, regional-scale (e.g., Gulf of Maine, Puget Sound) FEM models by creating offshore tidal boundary conditions. The regional models would use a grid based on the ocean-scale model, but with added refinements to capture smaller coastal features. Finally, for the sub-regional areas (bays and estuaries within a region), a practical approach would be to apply TCARI to those areas where there are sufficient tidal data and the datums produced by the regional model show significant errors. The datum fields would be corrected by applying TCARI to the error fields and adding the results to the original fields.

ACKNOWLEDGMENT

REFERENCES

Gill, S. K., and J. R. Schultz, 2001. Tidal Datums and Their Applications. Silver Spring, Maryland: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, <u>NOAA Special Publication</u> NOS CO-OPS 1, 111p. + appendix.

Hess, K. W., 2003 (in press). Water level simulation in bays by spatial interpolation

of tidal constituents, residual water levels, and datums. <u>Journal of Continental Research</u>.

Hess, K.W., 2002. Spatial interpolation of tidal data in irregularly-shaped coastal regions by numerical solution of Laplace's equation. <u>Estuarine, Coastal and Shelf Science</u>, 54(2), 175-192.

Hess, K.W., 2001. Generation of Tidal Datum Fields for Tampa Bay and the New York Bight. Silver Spring, Maryland: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, <u>NOAA Technical Report</u> NOS CS 11, 43p.

Hess, K.W., R. A. Schmalz, C. Zervas, and W. C. Collier, 1999. Tidal Constituent And Residual Interpolation (TCARI): A New Method for the Tidal Correction of Bathymetric Data. Silver Spring, Maryland: U. S. Department of Commerce, National Oceanic and Atmospheric Administration, <u>NOAA Technical Report</u> NOS CS 4, 99p.

Luettich, R. A., J. J. Westerink, and N. W. Scheffner, 1992. ADCIRC: an advanced three-dimensional circulation model for shelves coasts and estuaries, report 1: theory and methodology of ADCIRC-2DDI and ADCIRC-3DL, <u>Dredging Research Program Technical Report</u> DRP-92-6, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, 137p.

Milbert, Dennis G., 2002. Documentation for VDatum (and VDatum Tutorial); Vertical Datum Transformation Software. Version 1.06 (see http://chartmaker.ncd.noaa.gov/bathytopo/).

Mukai, A. Y., J. J. Westerink, and R. A. Leuttich, 2002. Guidelines for Using Eastcoast2001 Database of Tidal Constituents within Western North Atlantic Ocean, Gulf of Mexico and Caribbean Sea. <u>Coastal and Hydraulics Engineering Technical Note</u> CHETN-IV-40, U.S. Army Engineer Research and Development Center, Vicksburg, MS. 20p.

Myers, E. P., and A. M. Baptista, 2001. Inversion for tides in the Eastern North Pacific Ocean. <u>Advances in Water Resources</u>, 24, 505 – 519.

NOS, 1987. Delaware River and Bay Tidal Circulation and Water Level Atlas. National Ocean Service, NOAA. 49p.

Riley, J. L., and D. G. Milbert, 2003. Hydrographic surveying on a tidal datum with kinematic GPS:NOS case study in Delaware Bay. (this proceedings).

Smith, D. A., and D. R. Roman, 2001. GEOID99 and G99SSS: 1-arc-minute geoid models for the United States. <u>Journal of Geodesy</u>, 75, 469 – 490.